

Higgs Sector in Anomaly-Mediated Supersymmetry Breaking Scenario

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Abstract

In the minimal anomaly-mediated supersymmetry breaking (AMSB) model, a universal contribution m_0 to all the scalar masses is introduced in order to avoid the negative slepton mass problem. The Higgs spectrum and couplings are determined by four parameters: m_{aux} , m_0 , $\tan\beta$ and $\text{sign}(\mu)$. The sign of μ affects m_A at large $\tan\beta$ and m_h at small $\tan\beta$. The CP-odd Higgs mass m_A is usually much larger than m_Z and the lightest CP-even Higgs is simply analogous to the one in the standard model. The current and future Higgs searches in LEP, Tevatron and LHC provide a test ground for the AMSB scenario. The current LEP bounds and LEP 192/196 preliminary results have already excluded a small m_0 and m_{aux} region for small $\tan\beta$. While the entire parameter space will be excluded if no Higgs is found at Tevatron RUN II with 2 fb^{-1} luminosity. However, if the AMSB scenario is true, a Higgs can be found at 5σ significance level at both Tevatron running at luminosity 10 fb^{-1} or higher and LHC.

1 Introduction

The mechanism for electroweak symmetry breaking (EWSB) remains a mystery after many years of effort on both the theoretical and experimental sides. In the standard model, the Higgs mechanism can give mass to all the known particles and is left with a fundamental scalar boson. The best fit to the electroweak precision measurements prefers a Higgs mass of $90 - 100 \text{ GeV}$ [1]. However, theoretically, there is no protection of this scalar mass and it can receive large radiative corrections from new physics at any high scale Λ (e.g. the GUT scale). It is thus a miracle that the cancellations between the large scales should be so complete as to give the preferred small Higgs mass.

Supersymmetry (SUSY) provides a good explanation of this hierarchy problem if the SUSY breaking scale is around 1 TeV. There are two Higgses H_u and H_d , which give masses

to up type quarks and down type quarks/leptons respectively. There are five Higgs bosons left after the EWSB: two CP-even Higgses h and H with $m_h < m_H$, one CP-odd Higgs A and two charged Higgses H^+ and H^- . Unlike the standard model, where basically no upper limit is put on the Higgs mass except the naturalness, the light CP-even Higgs mass m_h in the supersymmetric models is highly constrained. The tree level mass is lighter than m_Z , while the radiative corrections could change the result by 20 – 30 GeV. Lots of calculations have been done on the radiative corrections to m_h using different approximations such as the diagrammatic approach [2, 3], the renormalization group approach [4] and the effective potential method [5]. In this paper, we adopt the renormalization group improved one-loop effective potential method discussed in [6], including the important next-to-leading effects.

The newly proposed Anomaly-Mediated Supersymmetry Breaking (AMSB) scenario [19, 20] presented an alternate way to give mass to all the super particles. SUSY breaking happens on a separate brane and is communicated to the visible world via the super-Weyl anomaly. The overall scale of sparticle masses are set by m_{aux} , which is the VEV of the auxiliary field in the supergravity multiplet. In the minimal case, as will be explained in detail in the next section, the particle spectrum can be determined by 3 + 1 parameters:

$$\{m_{\text{aux}}, m_0, \tan\beta, \text{sign}(\mu)\}. \quad (1)$$

Here m_0 is some universal mass scale introduced at the GUT scale to solve the tachyonic slepton mass problem.

Some phenomenological implications of AMSB have been studied in the literature. There is a novel “focus point” behavior in μ [7, 8], which allows squark and slepton masses far above their usual naturalness bounds. Sleptons are nearly degenerate and highly mixed, while the squarks are universally very heavy [7, 9, 10]. The experimental signatures are sensitive to the hierarchy of sneutrino, slepton and Wino masses. In particular, the neutral Wino as the Lightest Supersymmetric Particle (LSP) scenario has been explored in detail in [11]. A disappearing charged track inside the detector serves as a distinctive experimental signal. A variety of low energy observables, including $b \rightarrow s\gamma$, the anomalous magnetic moment of the muon and the electric dipole moments of the electron and neutron, are sensitive probes of anomaly-mediated parameter spaces [7]. AMSB scenario has important cosmological consequences as well [9, 12]. The gravitino mass is much heavier than the mass of the other sparticles, which alleviate the cosmological problem associated with gravitino decays during nucleosynthesis. Furthermore, the neutral Wino-LSP can form the cold dark matter, because they are copiously produced from the primordial gravitino decays. However, no detailed presentation of the light Higgs phenomenology in the AMSB scenario has existed so far. It is thus necessary to study the Higgs sector and see how the current or the future experimental Higgs searches can constrain the AMSB parameter spaces.

The current experimental Higgs bound $m_{H_{SM}} > 95.2$ GeV [13] is set by the LEP combined searches at 189 GeV through the channel $e^+e^- \rightarrow ZH_{SM}$ where $H_{SM} \rightarrow b\bar{b}$ or $\tau\bar{\tau}$. A recent LEP updates at 192/196 GeV and 109 pb⁻¹ luminosity gave a preliminary limit of 98.7 GeV [13] on the standard model Higgs mass. After the final run of LEP at $\sqrt{s} = 200$ GeV, a lower limit of 108 GeV on the Higgs mass can be achieved if no Higgs is found [14]. In LHC [15], $pp \rightarrow \gamma\gamma + X$ has been studied. For a low luminosity of 30 fb⁻¹, a standard model Higgs

in the mass range $105 - 148$ GeV can be discovered at 5σ significance level. With higher luminosity 100 fb^{-1} , the reach can be extended to $80 - 160$ GeV. If other decay channels $H \rightarrow ZZ, ZZ^* \rightarrow 4l$, $H \rightarrow ZZ, WW \rightarrow 2l2\nu$, $H \rightarrow WW \rightarrow l\nu 2j$ are included, a reach of 600 GeV or even higher is possible.

In Tevatron RUN II and RUN III, the upgraded CDF/DØ will have greatly improved sensitivity in searching for the Higgs boson in both the standard and supersymmetric models[16]. For light standard model Higgs ($m_H < 135$ GeV), the dominant Higgs decay mode is $H \rightarrow b\bar{b}$. Four search channels have been studied: $l\nu b\bar{b}$ (WH events where $W \rightarrow l\nu$), $\nu\bar{\nu} b\bar{b}$ (ZH events where $Z \rightarrow \nu\bar{\nu}$), $l^+l^-b\bar{b}$ (ZH events where $Z \rightarrow l^+l^-$) and $q\bar{q}b\bar{b}$ (WH and ZH events with W and Z decaying to $q\bar{q}$ pairs). For heavier Higgs, $H \rightarrow WW$ dominates. A single Higgs production via gluon fusion gives $l^+l^-\nu\bar{\nu}$ final states. Higgs can also be produced in conjunction with a vector boson, where the search channels can be $l^\pm l^\pm jj$ or $l^\pm l'^\pm l^\pm$. Combining all the search channels from both experiments, the integrated luminosity needed to exclude the SM Higgs at 95% CL, or discover it at 3σ or 5σ level of significance, is given in [16]. In this paper, we use the results obtained by a neural-network-based analysis in separating the signals and background for each hypothesized Higgs mass.

The light SUSY CP-even Higgs mass is usually smaller than 130 GeV. Thus, the strategy for light standard model Higgs searches applies. The exclusion/discovery reaches of SUSY Higgses depend on both their masses and couplings to standard model gauge bosons, quarks and leptons. To parameterize it in a model independent way, R is introduced as

$$\begin{aligned} R &= \frac{\sigma(p\bar{p} \rightarrow Wh(\text{or } H))}{\sigma(p\bar{p} \rightarrow WH_{SM})} \frac{B(h(\text{or } H) \rightarrow b\bar{b})}{B(H_{SM} \rightarrow b\bar{b})}, \\ &= \sin^2(\beta - \alpha) \text{ (or } \cos^2(\beta - \alpha)) \frac{B(h(\text{or } H) \rightarrow b\bar{b})}{B(H_{SM} \rightarrow b\bar{b})}. \end{aligned} \quad (2)$$

In [16], the exclusion/discovery contours of a light CP-even Higgs in the space of R and m_h can be found for different integrated luminosities, combining both of the CDF/DØ results. These contours can be translated to the reaches in the SUSY parameter spaces for different SUSY scenarios.

The Higgs searches in the minimal Supersymmetric extension of the Standard Model (MSSM) scenario have been discussed in detail [17] for LEP, Tevatron and LHC. Although certain regions of the parameter spaces are difficult for some of the colliders, three collider experiments are complementary in searching for light Higgs bosons. The minimal Supergravity model (mSUGRA) and Gauge Mediated SUSY Breaking model (GMSB) [18] have also been examined for both Tevatron and LEP 2 Higgs searches. Almost the entire parameter spaces can be covered by various searching channels and stringent bounds can be put on these models once the proposed signals are not found.

The purpose of this paper is to work out the Higgs mass spectrum and the couplings to the standard model particles in the AMSB scenario. Combining the existing results of the Higgs searches, we can further constrain the AMSB parameter spaces. In Section 2, we will discuss the AMSB scenario in detail and see how the entire SUSY mass spectrum and Higgs couplings can be determined by the four parameters. In Section 3, we presented the numerical results for the Higgs masses in the parameter spaces of the AMSB scenario and

discuss their implications. The discovery/exclusion regions for Higgs searches in the AMSB parameter spaces are also presented, given the existing Higgs search results in the literature. We reserve the last section for conclusions and discussions.

2 Calculations

In the AMSB scenario, the low energy soft supersymmetry breaking parameters M_i (gaugino masses, $i=1-3$), m_{scalar}^2 and A_y at the GUT scale are given by [19, 9]

$$M_i = \frac{\beta_{g_i}}{g_i} m_{\text{aux}}, \quad (3)$$

$$m_{\text{scalar}}^2 = -\frac{1}{4} \left(\frac{\partial \gamma}{\partial g} \beta_g + \frac{\partial \gamma}{\partial y} \beta_y \right) m_{\text{aux}}^2 + m_0^2, \quad (4)$$

$$A_y = -\frac{\beta_y}{y} m_{\text{aux}}. \quad (5)$$

Notice that the slepton squared-masses would be negative if m_0 is absent. There have been several proposals to solve this tachyonic slepton problem: the bulk contributions [19], the non-decoupling effects of ultra-heavy vectorlike matter fields [21], coupling extra Higgs doublets to the leptons [22] and the heavy mass threshold contribution at higher orders [23]. Here we just adopted a phenomenological approach and introduced an additional mass scale m_0 at the GUT scale in order to keep the slepton masses positive [9]. For simplification, we choose m_0 to be the same for all the super scalar particles. The deviation from this approach will be discussed in Section 4.

Eq. (3), (4) and (5) would be true at all scales if m_0 is absent. However, once m_0 is introduced at the GUT scale, the above definitions of M_i , m_{scalar}^2 and A_y set the boundary conditions and the entire SUSY spectrum can be obtained via the running of supersymmetric Renormalization Group Equations (RGE) down to a lower scale.

Once we cross the squark threshold, the squarks decouple and we are left with an effective field theory with two Higgses and all the standard model particles¹. The two unknown parameters $|\mu|$ and b can be determined by the minimization of the Higgs effective potential [24] at the electroweak scale once we specify the value of $\tan \beta$ and the sign of μ .

The radiative corrections to the Higgs mass are important and can be as large as 20 – 30 GeV. In this paper, we use the renormalization group improved one-loop effective potential approach, including the important next-to-leading effects [6]. One modification to [6, 10] is that in the large $\tan \beta$ case, the bottom mass corrections to the bottom Yukawa coupling have been taken into account[17]:

$$y_b = \frac{m_b}{v \cos \beta (1 + \Delta(m_b))}. \quad (6)$$

¹Gluinos are also decoupled since their masses are close to the squark masses. The contributions of Bino and Winos to the Higgs sector can be neglected since the $U(1)_Y$ and $SU(2)$ gauge couplings are small.

$\Delta(m_b)$ includes the one-loop contributions from gluino-sbottom and higgsino-stop[25]:

$$\Delta(m_b) \sim \frac{2\alpha_3}{3\pi} M_{\tilde{g}} \mu \tan \beta I(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_{\tilde{g}}) + \frac{Y_t}{4\pi} A_t \mu \tan \beta I(M_{\tilde{t}_1}, M_{\tilde{t}_2}, M_{\tilde{\mu}}), \quad (7)$$

where $\alpha_3 = g_3^2/4\pi$, $Y_t = y_t^2/4\pi$ and the function I is given by

$$I(a, b, c) = \frac{a^2 b^2 \ln(a^2/b^2) + b^2 c^2 \ln(b^2/c^2) + c^2 a^2 \ln(c^2/a^2)}{(a^2 - b^2)(b^2 - c^2)(a^2 - c^2)}. \quad (8)$$

In our conventions, $m_{\tilde{g}}$ and A_t are both negative, while I is positive by definition. Thus, for negative (positive) μ , the correction to bottom mass is positive (negative), which decreases (increases) the bottom Yukawa coupling. This has an important impact for m_A , as will be shown in Section 3. Also, we choose to look at the Higgs mass at the scale of on-shell top quark mass $\bar{m}_t = m_t(m_t)$ because the two-loop corrections are small at that scale [6].

Therefore, the Higgs mass spectrum is fixed once we know the values of m_{aux} , $m_0 \tan \beta$ and the sign of μ . The couplings of Higgs particles to the other particles can be obtained by the diagonalization of the Higgs mass matrices.

3 Results

As was pointed out already in [7, 8], there is a ‘focus point’ behavior of μ in the large $\tan \beta$ region. Though μ stays below 1 TeV, m_0 can be 2 TeV or even larger. So we choose our parameter ranges to be from 0 to 2 TeV for m_0 , and from 20 TeV to 100 TeV for m_{aux} , which corresponds to a wino mass 58 GeV – 290 GeV.

Figure 1 shows the contours of the CP-odd Higgs mass m_A in the parameter space of m_0 and m_{aux} , for two values of $\tan \beta=3, 30$. For small $\tan \beta$, changing the sign of μ does not change the value of m_A . While for large $\tan \beta$, m_A decreases for positive μ . This is because for large $\tan \beta$, m_b corrections to the bottom Yukawa coupling become important. Moreover, y_b decreases (increases) for negative (positive) μ and m_A is given by

$$m_A^2 = m_{H_d}^2 + m_{H_u}^2 + 2\mu^2 + \text{radiative corrections}. \quad (9)$$

The values of $m_{H_d}^2$ and $m_{H_u}^2$ at a lower scale are determined by the RGE running from the GUT scale:

$$\frac{d}{dt} m_i^2 \sim \frac{1}{16\pi^2} \left[\sum_j Y^2 m_j^2 - g^2 M_{\text{gaugino}}^2 + Y^2 A^2 \right], \quad (10)$$

where the sum is over all the fields ϕ_j interacting with ϕ_i through the Yukawa coupling Y . Notice that the contributions from the terms proportional to the Yukawa coupling are always negative when running down from the GUT scale. In the AMSB scenario, $m_{H_d}^2 > m_{H_u}^2$ due to the large negative contributions to m_{H_u} from the $y_t^2 m_j^2$ terms. Therefore, m_A is mainly determined by $m_{H_d}^2$, which is larger for smaller y_b . For small $\tan \beta$, y_b is already small and this effect becomes less important.

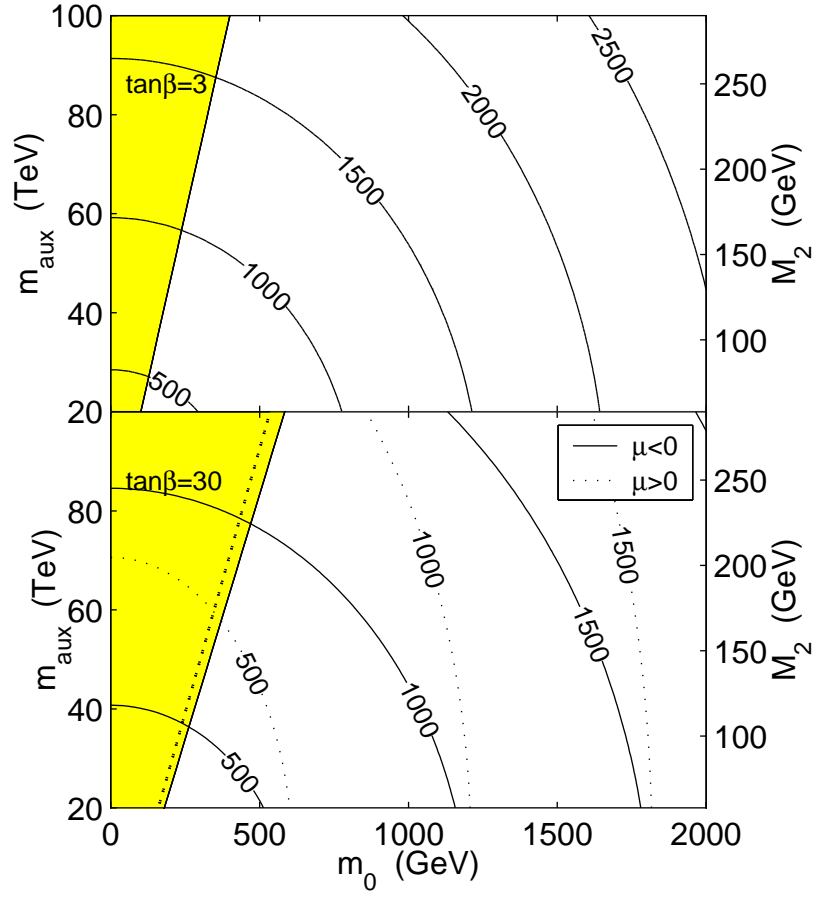


Figure 1: m_A contours for $\tan\beta = 3, 30$. For the upper plot, the results are the same for both signs of μ . The shaded region is excluded by the negative slepton masses.

	LEP			Tevatron (RUN II, III)			LHC
	189 GeV current	192/196 GeV 109 pb ⁻¹	200 GeV 200 pb ⁻¹	2 fb ⁻¹	10 fb ⁻¹	20 fb ⁻¹	
95% Exclusion	95.2	98.7	108	120	183.5	190	105-148
5 σ Discovery	none	none	106.5	none	109.5	123	

Table 1: 95% CL exclusion/5 σ discovery limits on SM Higgs mass for LEP, Tevatron and LHC colliders.

The shaded region in the upper-left corner is excluded by the negative slepton masses, which would disappear if we drop the assumption of the common mass m_0 for all the super scalar particles, as will be discussed in Section 4. In addition, for large $\tan\beta$ and positive μ , small m_A region (for $\tan\beta=30$, $m_A < 900$ GeV) is already excluded by $b \rightarrow s\gamma$ constraints [7].

Notice that m_A is usually larger than 500 GeV, which can greatly simplify our analysis. For $m_A \gg m_Z$, the low energy effective field theory looks like the standard model with one Higgs boson

$$h \simeq H_{\text{SM}} = H_1^0 \cos\beta + H_2^0 \sin\beta. \quad (11)$$

In particular, the couplings of hWW , hZZ and $hb\bar{b}$ are the same as the standard model values. All the results drawn from the standard model Higgs can be directly applied to this light Higgs. Most relevantly, the exclusion/discovery contours in the AMSB parameter spaces from the Higgs searches precisely coincide with the mass contours of m_h .

Table 1 summarizes the LEP, Tevatron and LEP reaches in the Higgs mass, either to exclude it at 95% CL or to discover it at 5 σ level of significance[13, 14, 15, 16, 17].

For small $\tan\beta = 3$, m_h is in the range of 96 GeV – 108 GeV (92 – 104 GeV) for $\mu < 0$ ($\mu > 0$). Current LEP bounds have already excluded a small m_0 and m_{aux} region for $\mu > 0$. The preliminary results of LEP running at 192/196 GeV can exclude the parameter region up to $m_{\text{aux}} = 47$ TeV ($m_{\tilde{w}} = 137$ GeV) and $m_0=1440$ GeV for $\mu > 0$, while only a tiny region for $\mu < 0$. The entire region can be excluded if no Higgs is found after the LEP final run at 200 GeV. However, if an AMSB Higgs does exist, the first chance to discover it is at LEP 200. We can explore m_{aux} up to 74 TeV (corresponding to $m_{\tilde{w}} = 215$ GeV) with $\mu < 0$. While for $\mu > 0$, the entire parameter space will be covered. Therefore, the AMSB scenario can be examined for the small $\tan\beta$ case in the next few years of LEP measurements.

Tevatron experiments have great discovery potential for the Higgs boson. Even at the lowest integrated luminosity 2 fb⁻¹, the AMSB scenario will be excluded if no Higgs is found. For luminosity 10 fb⁻¹ or even higher, a CP-even light Higgs will be found in a natural parameter space of AMSB. The contour of LHC discovery should be read differently. Only the region above the LHC 5 σ discovery contour will be covered by LHC Higgs searches at 30 fb⁻¹. This is because $pp \rightarrow \gamma\gamma + X$ is only sensitive to the Higgs mass in the range of 105 – 148 GeV at that luminosity. Only part of the parameter space in $\mu < 0$ case, nearly $m_{\text{aux}} > 53$ TeV ($m_{\tilde{w}} > 153$ GeV), will be discovered and $\mu > 0$ will remain untouched. Of course the entire parameter space can be explored by LHC with luminosity 100 fb⁻¹.

The story is quite different for large $\tan\beta$. The difference in m_h caused by the sign

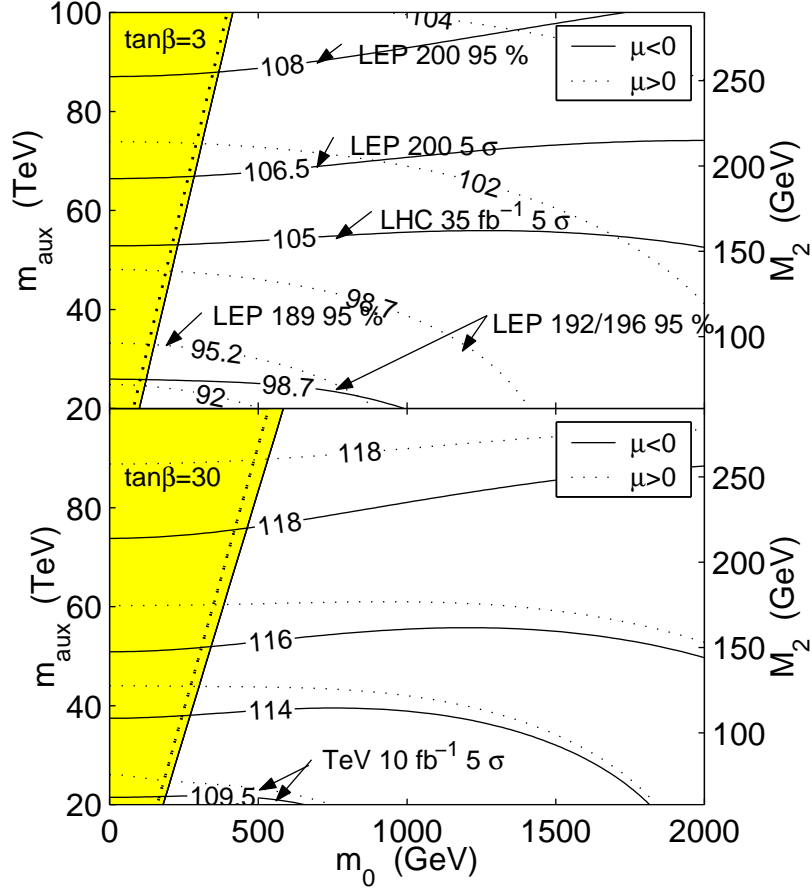


Figure 2: m_h contours for $\tan\beta = 3, 30$. The shaded region is excluded by the negative slepton masses. The region below the mass contours would be excluded or discovered by different experiments, except for the LHC discovery contour, where the region above the contour would be discovered.

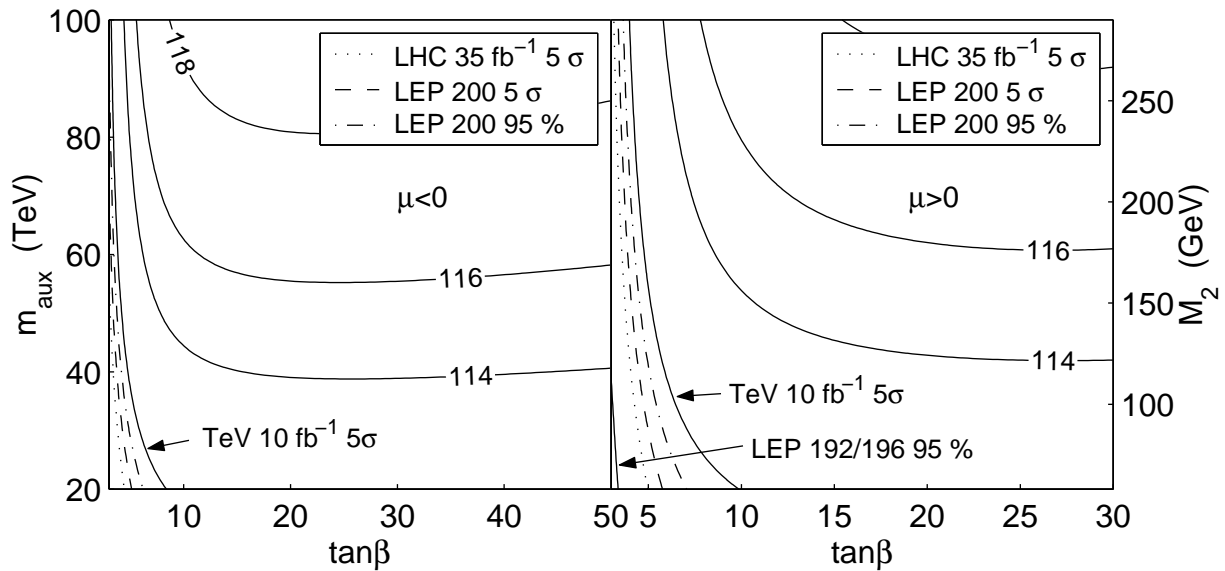


Figure 3: m_h contours for $m_0 = 1000$ GeV. The region below the mass contours would be excluded or discovered by different experiments, except for the LHC discovery contour, where the region above the contour would be discovered.

of μ is not so critical now. This is because μ only comes in through the combination $\tilde{A}_t = A_t - \mu/\tan\beta$. The second term is much smaller at large $\tan\beta$. In average, m_h is about 10 GeV larger than the small $\tan\beta$ case, which eliminates its chance to be excluded or discovered at LEP. Tevatron running at 2 fb^{-1} will exclude the entire parameter space if no light Higgs is found. However, to discover a Higgs at 5σ significance level, we have to wait till Tevatron RUN III at 20 fb^{-1} integrated luminosity or the running of LHC.

To further understand the difference in the Higgs search reaches due to $\tan\beta$, we present the mass contours for m_h in $m_{\text{aux}} - \tan\beta$ plane, with $m_0 = 1$ TeV (Figure 3). For $\mu > 0$, we only study $\tan\beta < 30$ due to the constraints from $b \rightarrow s\gamma$. LEP at $\sqrt{s} = 200$ GeV can only exclude a very small corner up to $\tan\beta = 6$ ($\tan\beta = 7$) for negative (positive) μ . We have to wait until the Tevatron starts its RUN II to fully exclude the entire region if no Higgs is found. At the same time, to discover a Higgs, it is only possible for LEP 200 when $\tan\beta < 5 - 6$ or Tevatron at 10 fb^{-1} when $\tan\beta < 8 - 10$. Only Tevatron operating at an integrated luminosity larger than 20 fb^{-1} can cover the entire space. LHC with luminosity 30 fb^{-1} can not explore the low $\tan\beta$ region. With higher luminosity or in combination with other search channels, the entire region can be studied.

4 Conclusions and Discussions

The minimal AMSB scenario is a well defined low energy effective field theory with all the SUSY spectrum determined by the four parameters : $m_{\text{aux}}, m_0, \tan\beta$ and $\text{sign}(\mu)$. The sign of μ changes the results of m_A at a large $\tan\beta$ and m_h at a small $\tan\beta$. The Higgs sector in this model is simplified because $m_A \gg m_Z$. The lightest CP-even Higgs is standard-model-like

with mass in the range of 92 – 118 GeV. Current and future experiments in LEP, Tevatron and LHC have great potential to constrain this scenario. If no Higgs is found in LEP 200, the low $\tan\beta$ region will be excluded. Furthermore, if no Higgs is found after Tevatron RUN II at 2 fb^{-1} , the AMSB scenario will be totally excluded. However, if AMSB is true, a light Higgs will first be detected at 5σ significance level for low $\tan\beta$ case at LEP 200. Tevatron running at luminosity of 10 fb^{-1} will discover a light Higgs if $\tan\beta$ is small. Once Tevatron reaches its RUN III at 20 fb^{-1} , or LHC turns on, almost the entire parameter space of the AMSB scenario will be explored and a signal of Higgs would not escape detection.

Comparing with the reaches of LEP, Tevatron and LHC for Higgs searches in MSSM, mSUGRA and GMSB [17, 18], we can see that the Higgs sector in AMSB scenario corresponds to the heavy m_A case in MSSM. Similar to mSUGRA and GMSB, low $\tan\beta$ region can be probed at LEP or at Tevatron running with lower luminosity, while the whole parameter space would be explored at Tevatron with higher luminosity and at LHC.

As mentioned above, here we choose a common mass m_0 for all the super scalar masses in our analysis. This is a simplified assumption and is not generically true. As the lepton-slepton sector and first two generations do not contribute much to the Higgs sector (due to the small Yukawa couplings), our results will remain true if the sleptons and the first two generation squarks have totally different positive contributions. The upper-left shaded region in $m_{\text{aux}} - m_0$ spaces that was excluded before because of the negative slepton masses can now be restored (the continuity of the mass contours are also shown). Furthermore, the positive contributions to m_{H_d} and m_D can be different from those to m_{H_u} and $m_{Q,U}$, while m_h remains almost the same. This is because for $m_A \gg m_Z$, m_h is determined by $\tan\beta$ and the radiative sector from the stop sector, which is related to m_Q , m_U and at small $\tan\beta$, to μ . Furthermore, m_D affects μ through m_{H_d} , as the running of RGEs are coupled (see Eq. 10). However, the bottom Yukawa coupling at small $\tan\beta$ is small, which partly weakens the influence of m_D on m_{H_d} , and further on μ and m_h . The effect of m_{H_d} to μ is small due to the $1/(\tan^2\beta - 1)$ factor in front of $m_{H_d}^2$ in determining μ :

$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}m_Z^2. \quad (12)$$

Nevertheless, m_A would be changed if m_{H_d} and m_D take a different value of m_0 . For the large $\tan\beta$ case, we can further change m_0 in m_{H_u} while keeping m_h to be almost the same. In this case, m_{H_u} comes into effect through μ , whose effect is small for large $\tan\beta$. Thus, our conclusions will remain true if we take m_0 to be the common mass correction only to m_Q , m_U and for small $\tan\beta$ also to m_{H_u} . Even if all the additional positive contributions to the scalar masses are different, our analysis can still be applied as the only changes are in the boundary conditions. Of course in this case, we have more parameters and the reaches in the parameter spaces from Higgs searches become a bit more complicated.

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